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Trade-off between sound insulation performance and cost-optimality in a residential nZEB

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Abstract

Until now, design of new high performance buildings has been focused on the energy performance but lacks to be addressed as a holistic problem taking into account all the aspects of a performance of a building. This work strives to study and optimize at once, the energy performance of a building and the sound insulation performance of its facades. In particular, energy and acoustic performances of different building facades, made of two different wall types, were compared taking in account the cost-optimized design of a building. The proposed methodology couples a cost-optimization of the building energy model made though TRNSYS® and GenOpt, with an evaluation of the sound insulation indexes with Matlab®, and it was applied to a French single-family case study. The results show that the cost optimal energy performance level of such case study is somewhere between 40 and 47 kWh/m².year, while the sound insulation efficiency of the façade can reach a wide range of values. However, the proposed methodology allowed to highlight several design solutions fulfilling the requirements in term of energy, cost and acoustics performances.

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Keywords: Cost optimal analysis, nZEB, Sound insulation; façade; envelope; simulation-based optimization; TRNSYS; Matlab; GenOpt.

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1. Introduction

Until now, the nZEB target has focused the attention of researchers and professionals on the energy performance of buildings, leaving aside other types such as sound insulation, daylighting, fire safety, etc. In fact, analyses are now carried out independently for each domain – energy [1], sound [2], light – thus limiting the more effective holistic approach of building design. Methods and tools able to consider those requirements together are needed and it is worth researching on this subject. Examples of this overall approach can be found, in specific cases like the coupling between the lighting (natural and artificial) energy use and the energy performance in buildings.

Two different European Directives consider the energy and the sound insulation performances. These are respectively, 2010/31/UE [3] for energy performance and 2002/49/EC [4] for assessment and management of environmental noise. The first one has introduced the principle of cost optimization in the building energy design. In fact, the cost-optimal energy performance level is the one related to the minimum global cost. But the design of a nZEB is tightly linked to its environment. Plenty of criteria are involved such as climate, available technical systems, typology of the building, and properties of construction [5]. In current literature, most studies deal with the cost-optimization, but none has considered the influence of high sound insulation performance of facades, which is one of the most important evaluation criteria of the building envelope.

The purpose of this work is to investigate the trade-off between energy and acoustic performances of different building facades, with the final aim of comparing the cost optimization in term of energy with the sound insulation performance of the building envelope and provide the most efficient solution.

The proposed framework is based on the coupling between a dynamic building simulation tool and an optimization tool. A building energy model is created and calibrated on a dynamic energy simulation software. Energy efficiency measures concerning different technologies and envelope systems, characterized by different sound insulation performances were evaluated.

Nomenclature

C	Spectrum adaptation term 1 in accordance with EN-ISO 717-1, dB
C_{tr}	Spectrum adaptation term 1 in accordance with EN-ISO 717-1, dB
$D_{nT,A,tr}$	Corrected weighted standardized sound level difference of a facade in accordance with EN-ISO 717-1, dB
$D_{2m,nT,w}$	Weighted standardized sound level difference of a facade in accordance with EN-ISO 717-1, dB
R	Sound reduction index of a component of a facade, dB
R_m	Mean sound reduction index of a portion of a facade, dB
S	Surface of an element, m²
T_0	Reference reverberation time, given as 0.5s, s
V	Volume of the receiving room, m^3

2. Methodology

2.1. The cost-optimal analysis

The concept of cost-optimality was introduced in Europe by the Energy Performance of Buildings Directive [3], stating that “MS [EU Member States] must ensure that minimum energy performance requirements are set with a view of achieving at least cost-optimal levels for buildings, building units and building elements”.

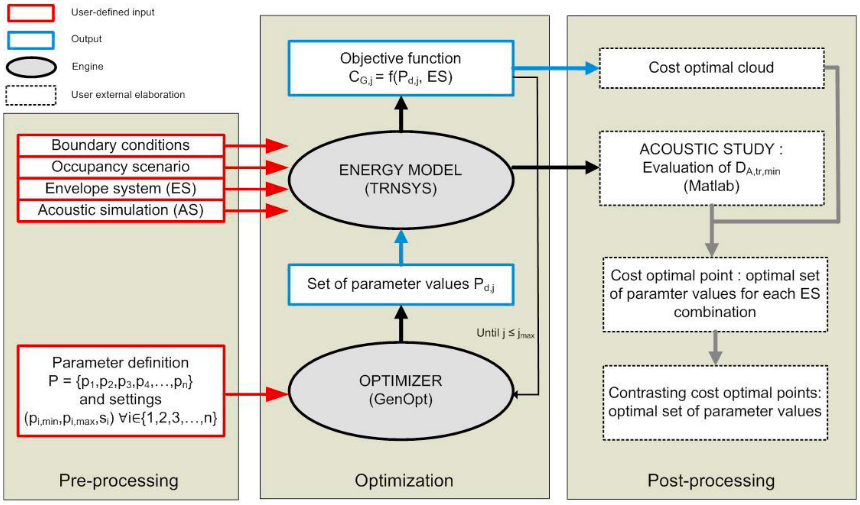

Fig. 1. Schematic of the methodology

The cost-optimality approach [7, 8] was adopted as a driving criterion for designing nearly Zero Energy Buildings [9], leading to evaluate the energy performance level related to the minimum global cost over the economic lifecycle and investigate technologies and policies for moving the cost-optimal point towards better energy performance levels.

The main steps of the methodology involve the selection of energy efficiency measures to be applied to the reference building, RBs, the assessment of energy performance and the calculation of global cost. The calculation is related to each selected package of energy efficiency measures. Following the procedure described in the European Standard EN 15459 [10], the global cost formula can be written as:

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \cdot R_d(i) \right) - V_{f,\tau}(j) \right] \tag{1}$$

where C_G (τ) represents the global cost relatively to the starting year τ_0, considering a number τ of years as the calculation period, C_I is the initial investment cost, $C_{a,i}$ (j) is the annual cost for component j at the year i (including running costs and periodic or replacement costs), R_d(i) is the discount rate for year i, $V_{f,\tau}$ (j) is the final value of component j at the end of the calculation period (relatively to the starting year τ_0). The cost optimal solution is the one corresponding to the minimum global cost.

For the purpose of the present work, the global cost equation was selected as the objective function for the optimization process. The calculation period was set to 30 years and the financial parameters for determining the discount rate were set as in [11].

2.2. The acoustic analysis

As shown in Figure 1, at the end of the cost optimization, the calculation of the acoustic indexes is done. The process runs on the software Matlab®. The input data, in particular the sound reduction indexes, R, in dB, of each component of the facade, are given by the user during the pre-processing phase.

The index $D_{nT,A,tr}$ referring to the French regulation on the acoustic characteristics of buildings [12], was selected as the sound insulation index in this study. It is named “weighted standardized sound level difference of the facade $D_{2m,nT,w}$, corrected by the spectrum adaptation term C_{tr}”. The adaptation term C_{tr} is a correction factor that is only used when the noise source is road traffic. This index is calculated for each building facade, specific to each room of a building.

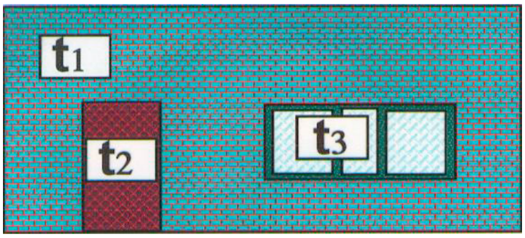

Fig. 2. Different components of a facade

A facade is composed by the wall, and possibly a window and a door, as shown in Figure 2. Each component, indexed by i, has its own sound reduction index R (in dB), given in one-third octave bands. In accordance with the Standard EN ISO 12354-3 [13], the mean sound index reduction R_m, at each third octave band, is given by

$$R_m = 10 \cdot \log\left(\sum_{i=1}^{n} S_i \Big/ \sum_{i=1}^{n} t_i \cdot S_i \right) \tag{2}$$

where t_i is equal to $10^{-Ri/10}$ and S_i is the surface of the component i.

Then, the standardized sound level difference of the facade $D_{2m,nT}$ can be calculated as

$$D_{2m,\,nT} = R_m + \Delta L_{fs} + 10 \cdot \log\left(\frac{V}{6 \cdot T_0 \cdot S} \right) - 2 \tag{3}$$

where ΔL_{fs} is the level difference due to the shape of the facade, V is the volume of the receiving room, T_0 is the reference reverberation time, which is 0.5 s and S is the total surface of the portion.

Starting from $D_{2m,nT}$ one-third octave band values, the weighted standardized sound level difference of the facade $D_{2m,nT,w}$ and the spectrum adaptation term C_{tr} can be evaluated following, using reference curves [14]. The addition of those two values gives the corrected weighted standardized sound level difference of the portion of the façade, $D_{nT,A,tr}$ This index is a single value, normalized in reverberation time and volume, and expresses the sound insulation behavior of one portion of facade. In France, this value has to be above 30 dB according to [12]. In order to assess the global sound insulation performance of the whole building and to fulfill the French legislative requirements on sound insulation, it was decided to consider the minimum $D_{nT,A,tr}$ value among the ones of the various facades/portions of facade of the case study building.

3. The case study building

The case study building is a real nZEB single-family building composed of two floors in a compact shape (Figure 3), so that the exchange surface with the outdoor environment is minimized. Located in Ambérieu-en-Bugey, in the French region of Rhône-Alpes, the house is representative of new high-performance single-family houses in that region and can be taken as a reference for cost-optimal calculations [15].

In the present work, energy efficiency measures related to the envelope system were evaluated, while the technical system was fixed to the existing one. It is an efficient HVAC system composed of an air-air reversible heat pump combined with an underground heat exchanger for pre-treating air and a mechanical dual flow ventilation system with heat recovery. See details in [16].

In order to calculate the energy performance of the different energy efficiency measures, a dynamic simulation model created in TRNSYS was used.

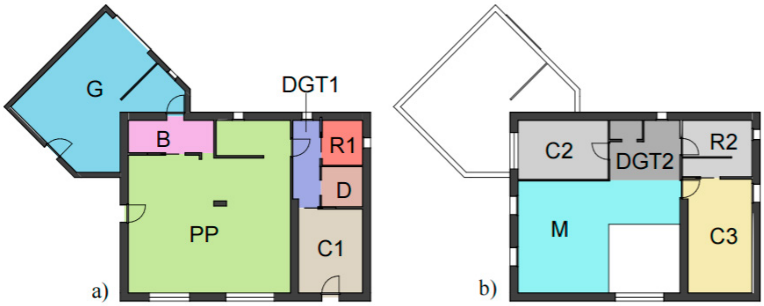

Fig. 3. Plans of the case study building. Ground floor (a), including the garage (G) the living room (PP) one bedroom (C1) and one restroom (R1);Second floor (b), including mezzanine (M), two bedroom (C2 and C3) and one restroom. Colors indicate the thermal zones of the simulation model [11]

3.1. The building envelope variables

In order to implement the cost-optimal methodology within a simulation-based optimization method, the energy efficiency measures were defined as optimization variables. Two different types of wall were implemented in the dynamic simulations:

- A lightweight wall named INTESA [18]. It is composed by two asymmetric cavities and various plasterboard layers. Densities of the plasterboards and air gaps of the cavities provide a high sound insulation while the cellulose flocks that fill the cavities provide the thermal insulation. Its weighted sound reduction index R_w (C, C_{tr}) is equal to 69 (-1, -4) and its U-value is equal to 0.21 W/m²K;
- A concrete wall composed by two lightweight concrete layers with different densities. Its weighted sound reduction index R_w (C, C_{tr}) is equal to 49 (-2, -5) and its U-value is equal to 0.41 W/m²K.

The sound reduction indexes of those two walls were taken from laboratory certificates, following to [19].

In the case study building, the four whole facades have been divided into 19 portions. Hence, 19 values of $D_{nT,A,tr}$ were evaluated in the post processing stage.

The two walls are two options assigned to the design variable "WallType". As shown in Table I, the lightweight INTESA wall is denoted by L, while the letter C indicates the concrete wall. The other variables are related to the thermal resistances of insulation of the roof and the slab (ResR and ResS, respectively), to the type of window depending on their orientations (WT, WTS, WTR) and to the dimension of windows (Blr, Bm, Hr). The range and the step for values to be assigned to each variable are reported in Table I, together with specification of the windows characteristics. One package of energy efficiency measures is defined as the combination of values assigned to each variable that define one building design configuration.

3.2. Cost functions

As described before, the global cost function is the objective function driving the optimization process. In order to calculate its value related to each package of energy efficiency measures, cost functions were associated to each variables, referring to the French market.

The costs assigned to the walls were provided by the manufacturer, as well as for the window cost functions. Roof and slab related cost functions were taken from the French Batiprix price list. Table II gives a summary of all the installation cost (CI) functions used in the present paper. Details about the creation of the cost functions can be found in [20].

Table 1. Definition of optimization variables

Parameter name and description	Unit	Min	Max	Step
WallType – Wall construction type		Light – L or Concrete - C		
ResR- Thermal resistance of roof insulation layer	[m²K/W]	0.9	18	0.25
ResS - Thermal resistance of slab insulation layer	[m²K/W]	0.9	18	0.25
WT - Window Type of North - East -West walls	[-]	1	4	1
WTS - Window Type of South wall	[-]	1	4	1
WTR - Window Type of Roof	[-]	1	4	1
Blr - Ground floor south window width (h= 2.15 m)	[m]	2.20	7.80	0.20
Bm - First floor south window width (h= 0.80 m)	[m]	0.20	7.80	0.20
Hr - Roof window height (w= 2.28 m)	[m]	0.00	4.7	0.58
Window type specification		U-value (W/m²K)	g-value	
1 - Double glazing	4/16/4	2.00	0.70	
2 - Double glazing, low emissivity with Argon	4/16/4	1.43	0.58	
3 - Triple glazing	4/16/4/16/4	0.70	0.50	
4 - Triple glazing, with Argon	4/16/4/16/4	0.40	0.40	

Table 2. Definition of cost functions

Wall cost function = f(WallType, Bm, Blr)	$CI_{wall} = 125.36 \cdot A_{outwall}$ for the light wall $CI_{wall} = 157.40 \cdot A_{outwall}$ for the concrete wall
Roof cost function = f(ResR, Hv)	$CI_{roof} = (43.478 \cdot ResR^{0.309} + 105.30) \cdot A_{roof}$
Slab cost function = f(ResS)	$CI_{slab} = (38.115 \cdot ResR^{0.186}) \cdot A_{slab}$
Window 1 = f(Bm, Blr, Hv)	$CI_{w1} = 349 \cdot A_{w1} + 28$
Window 2 = f(Bm, Blr, Hv)	$CI_{w2} = 390 \cdot A_{w2} + 29$
Window 3 = f(Bm, Blr, Hv)	$CI_{w3} = 454 \cdot A_{w3} + 36$
Window 4 = f(Bm, Blr, Hv)	$CI_{w4} = 470 \cdot A_{w4} + 36$
Energy cost (electricity)	0.0795 €/kWh_{night}+ 1.224 €/kWh_{day}

4. Results

Results are shown in a cost-optimal diagram (Figure 4) where the global cost (the objective function) is reported as a function of the primary energy consumption (kWh/m²y). The conversion factor between electricity and primary energy is the French one, which is 2.58. Both values are normalized to the floor area of the heated volume (155 m²). The discussion will be focused on the cost-optimal results first, then on the sound insulation performances and finally on the trade-off be-tween those two criteria.

4.1. Cost-optimal results

The evaluated building configurations can be represented in a cloud of points (Figure 4), where each point refers to a specific design of the case study building, and corresponds to a set of parameters values. The blue dots refer to the buildings with the light opaque wall whereas the red-yellow dots refer to the buildings with the concrete wall. The shades of colors represent the values of the weighted standardized sound insulation factors $D_{nT,A,tr}$.

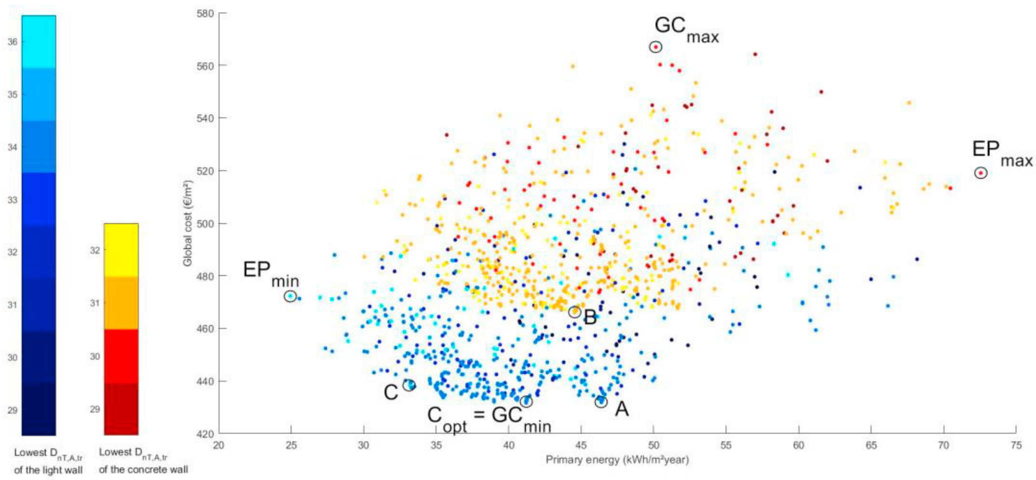

Fig. 4. Cost optimal representation of both walls

As shown on Figure 4, all the points of the clouds are within a range of energy performance that varies from 24.9 kWh/m² to 72.6 kWh/m², while the global cost range varies from 431.7 €/m² to 567.0 €/m². Points such as the extreme values of cost and energy performance have been highlighted in the diagram of Figure 4. Those extreme values are only related to the set of simulations performed by the PSO algorithm. Therefore, they may not correspond to the highest/lowest possible values within of the space of the parameters. The parameters values of those extreme points are reported in Table III.

The cost optimal energy performance level can be found in a range between 40 and 47 kWh/m².year. In this range, two minimum values can be found for two buildings characterized in Table III. The global cost optimal is given by CI_{min}. Its energy performance is equal to 41.22 kWh/m².year for a global cost of 431.65 €/m². Point A is the second minimum global cost in the case of the light opaque facade.

Table 3. Values of parameters and objective function of the remarkable points

Variable	Unit	EP_{min}	GC_{max}	GC_{min}	EP_{max}	A	B	C
Walltype	[-]	L	C	L	C	L	C	L
ResR	[m²K/W]	16.2	16.2	1.8	1.8	1.8	1.8	1.8
ResS	[m²K/W]	10.8	10.8	1.8	0.9	0.9	0.9	7.2
WT	[-]	5	5	1	1	1	1	3
WTS	[-]	5	5	1	1	1	1	4
WTR	[-]	5	3	1	1	1	1	3
Blr	[m]	2.2	7.8	2.2	4.6	2.2	2.2	2.2
Bm	[m]	2.5	6.3	0.2	7.8	0.2	0.2	0.2
Hr	[m]	0	4.7	0	4.7	0	0	0

From the energy consumption point of view, points A and GC_{min} are different, whereas their costs are sensibly the same. This difference is only due to the decrease of the thermal resistance of the slab. Therefore we can assume that the slab plays a major role in the energy consumption of the building.

Especially among the low global costs, the shapes of the two clouds are very similar. From the energy point of view, the concrete wall is less performing than the light wall since a shift of about 5 kWh/m² can be observed. This is due to the difference in the U-values between the two walls (0.41 W/(m²K) for the first one and 0.21 W/(m²K) for the second one). Nevertheless, the set of parameters that defines point B, which represents the global cost minimum in the case of the concrete wall, is the same as the global cost minimum referred to the light wall. The difference in the energy performance is only due to the adopted type of wall. This set of parameters can be considered as the best, regardless the type of opaque facade.

4.2. Acoustic results

As regards the facade sound insulation performance (shades of blue and red in Figure 4), it can be noted that the concrete wall gives, in general, values of the minimum $D_{nT,A,tr}$ lower than the ones of the light wall. It has to be noted that in the vast majority of cases, the lowest $D_{nT,A,tr}$ can be attributed to the living room portion of the south facade.

Differences in the minimum $D_{nT,A,tr}$ are explained by the optimization process in which vary both the dimension and the type of the windows, thus resulting in different mean sound reduction values. In fact, most of the points of the concrete wall may not be acceptable according to the French law [12] regarding sound insulation of buildings. On the contrary, the light wall guarantees the minimum requirement for most of the analyzed points. This can be explained by the lower weighted sound reduction index of the concrete wall (51dB) in relation to the weighted sound reduction of the light wall (69dB). In both clouds, there is no clear correlation between sound insulation of the facade and global cost nor primary energy use.

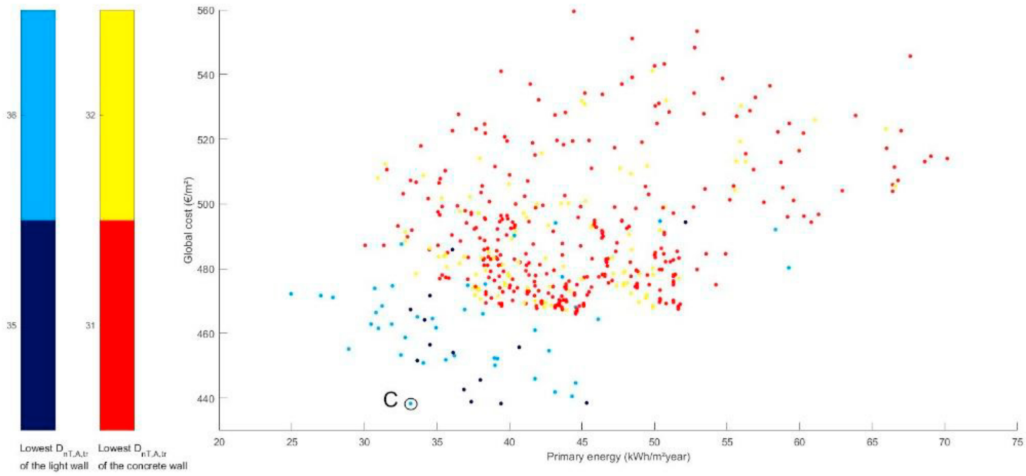

Fig. 5. Cost optimal representation of both walls

This can be appreciated from the fact that, especially for the concrete wall, quite different sound insulation values can be found for a given global cost value.

Furthermore, it can be noted that some points representing buildings with a very low sound insulation performance present a very high global cost, corresponding to design solutions that should be clearly discarded. The region of lowest global costs, for both walls, presents buildings with quite good values of sound insulation.

In order to focus the analysis on the best sound insulation performing facades, in Figure 5 only values higher than 34 dB for the light wall and higher than 30 dB for the concrete wall are reported.

In the neighborhood of the global minimum cost (+2 €/m²), some sets of parameters present low weighted standardized sound level difference of the facade. It is explained by a very high thermal resistance of the slab that gives a high energy performance, coupled by small double glazed windows filled with argon that give a very good sound insulation. Indeed, the bigger the windows are the more the noise is transmitted.

Other sets of parameters for which the $D_{nT,A,tr}$ is equal to 36 are remarkable in the range between 25 and 33 kWh/m². For those buildings, triple glazed windows, mostly on the south facade, are used and give better results from the energy point of view but a higher global cost.

As figured out by point C, shown on Figures 4 and 5, which parameters are described in table III, a negligible increase in the global cost (approx. 1.5%) may lead to a better sound insulation and significant improvements in energy performance (- 19.5 %). This set of parameters may be chosen as the best trade-off between the three different objectives. The type of window may also be improved by the use of laminated-glass windows. They may provide much better acoustic performances even though the cost will necessarily increase.

5. Conclusions

This work has established a methodology for coupling sound insulation performance, cost optimization and energy performance. Nevertheless, in the sound insulation performance analysis, it should be noted that the driving aspect of the global cost optimization function is a compromise between the best thermal performance of the building and the lowest installation cost. Further studies may therefore be developed in order to include in the objective function the sound insulation requirement as well. In order to do so, appropriate functions for evaluating the sound reduction index of walls and windows should be implemented into the optimization process.

Further investigations may also be conducted regarding the sound reduction index of the opaque walls. Contrarily to the energy performance which is given by a single index, the sound insulation is represented by as many indexes as the number of portions of facades. Indeed, the index used in this paper was chosen as the minimum index of all the portions of the envelope, whereas a different choice such as a ponderation on the occupancy scenario of the rooms would be more representative of the global sound insulation behavior of the envelope.

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